



## Original Research Paper

## Engineering

# DC Motor Operation Controlled from A DC/DC Power Converter in Pulse Mode with Low Duty Cycle

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**ABSTRACT**

In this paper pulse mode of operation of DC motor controlled by DC/DC power converter is analyzed. DC motor operation with time intervals in which the motor operates without output load is of interest. In this mode it is possible the motor to restore energy. Also, in the paper are represented calculations for the amount of the restored energy in the pulse mode operation of the motor for different duty cycles

**KEYWORDS**

DC motor, DC/DC power converter, duty cycle, pulse mode

**INTRODUCTION**

Often in practice DC motor is supplied by a DC voltage, obtained from unregulated rectifier or accumulator batteries. In this case, DC motor operates at rated speed, determined by the rotor voltage. In case for need speed control, the DC motor is supplied by regulated rectifier or DC/DC power converter (chopper) [1]-[4].

In Fig. 1 is shown a circuit of a DC motor controlled by DC/DC power converter which is commonly used and analyzed in [1], [2]. The output voltage  $u_M(t)$  depends from the gate pulse width  $t_i$  (excitation pulse) and switching period  $T_s$  ratio. Thus, the duty cycle of the DC/DC converter is defined as  $k = t_i/T_s$ . By changing the width of the pulse  $t_i$  (i.e. by changing the duty cycle  $k = t_i/T_s$ ) the average voltage of the motor  $u_M(t)$  is changed.

In Fig. 2 are shown the waveforms of the input current  $i_{sw}$  of DC/DC converter which is same with current through the transistor T (Fig. 2a), the current through the diode  $i_D$  (Fig. 2b), the current through the motor  $i_M$  (Fig. 2c), and the output voltage of the motor  $u_M$  (Fig. 2d) for duty cycle  $k = 0.9375$ . The waveforms are obtained with simulations of the circuit represented in Fig.1 in the software package PowerSim [5].

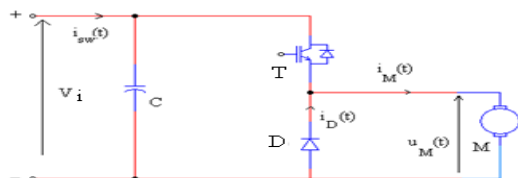


Figure1: Circuit of DC motor controlled by DC/DC power converter

Fig. 2c shows that for the topology represented in Fig. 1, the current through the DC motor is a result of the current through the transistor and the current through the diode. This is a classic case of DC

motor control with DC/DC converter analyzed in [1]-[4], [6].



Figure 2: Waveforms of the currents and the voltage in the DC/DC converter: a) input current  $i_{sw}$ , b) current through the diode  $i_D$ , c) current through the motor  $i_M$  and d) output voltage for duty cycle  $k = 0.9375$ .

The operation of the DC motor that has idle time intervals and restores energy (regenerative energy) is represented in [7]. Operation of a DC motor with variable duty cycle and the amount of energy that the motor restores at different duty cycles are not in scope of this paper.

This paper emphasizes the operation of the DC motor in pulse mode and low duty cycle. Analyses are performed when DC motor is supplied by a pulse voltage with lower amplitude and a greater duty cycle and pulse voltage with greater amplitude and lower duty cycle. In both cases analyzes are made when the motor is with and without output load. For this purpose, the topology of the DC/DC converter shown in Fig. 3 is used.

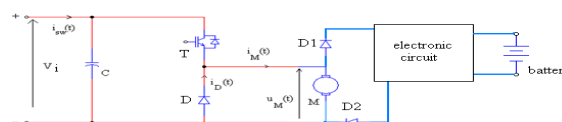


Figure 3: DC motor controlled by DC/DC power converter and integrated electronic circuit for collecting the regenerative energy from the motor

The DC/DC converter in Fig. 3 is connected with two diodes and an electronic circuit block. This circuit is turned on in time intervals when the transistor T is turned off. With this, it is possible to collect the

regenerative energy which the motor has stored previously. This energy is then stored in the battery B.

In Fig.4 are shown experimentally obtained waveforms of the voltage  $u_M(t)$  (channel 1) and the current  $i_M(t)$  (channel 2) of the DC motor in case when the motor is controlled by a DC/DC power converter with duty cycle  $k = t_i/T_s$  and the built electronic block as in Fig. 3.

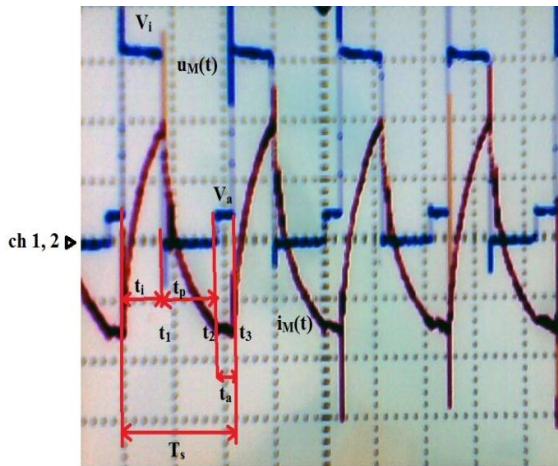


Figure 4: Waveforms of the voltage  $u_M(t)$  (channel 1) and current  $i_M(t)$  (channel 2) of the DC motor, controlled by a DC/DC power converter: with duty cycle  $k = t_i/T_s$ , excitation pulse with duration  $t_i$ , amplitude  $V_i$  and frequency  $f_s$ .

The amplitude of the excitation voltage pulse is  $V_i$ , the frequency is  $f_s$ , (the period is  $T_s$ ), and the duration is  $t_i$ . The duration of the excitation pulse  $t_i$  is determined by the time in which the transistor in the DC/DC converter is turned on [4].  $t_p$  is the pause time, and  $t_a$  is the time interval in which the motor operates in regenerative mode, i.e. restores energy, or simply the motor operates as a generator and generates a voltage with amplitude  $V_a$ .

## OPERATION OF DC MOTOR IN PULSE MODE

Analyses are performed for mode in which the motor operates without output load. The power which the DC motor receives during one period is:

$$P_M(t) = \frac{1}{T_s} \int_0^{T_s} u_M(t) i_M(t) dt \quad (1)$$

Where  $T_s = 1/f_s$  is the period of the pulse,  $u_M(t)$  is the voltage of the motor and  $i_M(t)$  is the current through the motor. The power that the motor receives in the time interval  $t_i = t_i$  (in Fig. 4, the time in which the transistor in the DC/DC converter is turned on) is:

$$P_M(t) = \frac{1}{T_s} \int_0^{t_i} u_M(t) i_M(t) dt \quad (2)$$

In the time interval  $t_i$ , the voltage  $u_M$  has amplitude  $V_i$ , so that (2) gets the form:

$$P_{M,i}(t) = \frac{V_i}{T_s} \int_0^{t_i} i_i(t) dt \quad (3)$$

The waveform of the current  $i_i(t)$  in the time interval  $t_i$  can be approximated with an equation of straight line, i.e.:

$$i_i(t) = \frac{t}{t_i} [i_i(t_i) - i_i(0)] + i_i(0) \quad (4)$$

In (4),  $i_i(0)$  is the current of the motor at the moment  $t = 0$ , and  $i_i(t_i)$  is the current at the finishing moment of the time interval  $t_i$ .

If (4) is substituted in (3), after solving the integral, for the power which the motor receives from the power source in the time interval  $(0, t_i)$  is obtained:

$$P_{M,i}(t) = V_i \frac{t_i}{T_s} \left[ \frac{i_i(t_i)}{2} + \frac{i_i(0)}{2} \right] \quad (5)$$

In time interval  $t_a = t_3 - t_2$ , the motor operates in regenerative mode, i.e. restores energy. The voltage which the motor generates in this interval is  $u_a(t)$ , and the current is  $i_a(t)$ . The power which the motor restores in this interval can be determined from the equation:

$$P_a(t) = \frac{1}{T_s} \int_{t_2}^{t_3} u_a(t) i_a(t) dt \quad (6)$$

In time interval  $t_a$ , the voltage  $u_a(t)$  has amplitude  $V_a$  as shown in Fig. 4, and the current  $i_a(t)$  can be determined as the average of its values at the moments  $t_2$  and  $t_3$ :

$$I_a = \left[ \frac{i_a(t_2) + i_a(t_3)}{2} \right] \quad (7)$$

With this, (6) gets the form:

$$\begin{aligned} P_a(t) &= \frac{V_a}{T_s} \left[ \frac{i_a(t_2 + i_a(t_3))}{2} \right] \int_{t_2}^{t_3} dt = \\ &= \frac{V_a}{T_s} \left[ \frac{i_a(t_2 + i_a(t_3))}{2} \right] (t_3 - t_2) = \frac{V_a}{T_s} \left[ \frac{i_a(t_2 + i_a(t_3))}{2} \right] t_a \end{aligned} \quad (8)$$

The duty cycle  $k = t_i/T_s$  depends on the time interval  $t_i$ , in which the transistor in the DC/DC converter is turned on. For two values of the duty cycle  $k_1$  and  $k_2$  the corresponding time intervals  $t_i$  will be marked as  $t_{i,1}$  and  $t_{i,2}$ , the time intervals  $t_a$  will be marked as  $t_{a,1}$  and  $t_{a,2}$ , and the corresponding variables in (5) and (8) will be marked with indexes  $i,1$  and  $i,2$ . So, for value of  $k_1$ , for the power that the motor receives from the power source in the time interval  $t_{i,1}$ , from (5) is obtained:

$$P_{M,i,1} = V_{i,1} \frac{t_{i,1}}{T_s} \left[ \frac{i_{i,1}(t_{i,1})}{2} + \frac{i_{i,1}(0)}{2} \right] \quad (9)$$

And for the value  $k_2$ , the power that the motor receives in time interval  $t_{i,2}$  is obtained:

$$P_{M,i,2} = V_{i,2} \frac{t_{i,2}}{T_s} \left[ \frac{i_{i,2}(t_{i,2})}{2} + \frac{i_{i,2}(0)}{2} \right] \quad (10)$$

If (9) and (10) are divided the following equation is obtained:

$$\frac{P_{M,i,1}}{P_{M,i,2}} = \frac{V_{i,1} t_{i,1}}{V_{i,2} t_{i,2}} \frac{i_{i,1}(t_{i,1}) + i_{i,1}(0)}{i_{i,2}(t_{i,2}) + i_{i,2}(0)} \quad (11)$$

The power that the motor receives from the power source, depends on its mechanical load, and always will be same regardless of the duty cycle  $k$ , the time interval  $t_i$  and the amplitude  $V_i$ . This means that the value of (11) is always a unit. If  $k_1 < k_2$  then  $(t_{i,1} = k_1 T_s) < (t_{i,2} = k_2 T_s)$ , therefore from the equality of the received power of the motor in both cases, follows that  $V_{i,1} > V_{i,2}$  and  $(i_{i,1}(t_{i,1}) + i_{i,1}(0)) > (i_{i,2}(t_{i,2}) + i_{i,2}(0))$ .

For the value  $k_1$  from (8) for the power which the motor restores in the time interval  $t_{a,1}$  is obtained

$$P_{a,1} = \frac{V_{a,1}}{T_s} \left[ \frac{i_{a,1}(t_2) + i_{a,1}(t_3)}{2} \right] t_{a,1} \quad (12)$$

For the value  $k_2$  from (8), for the power which the motor restores in time interval  $t_{a,2}$  is obtained:

$$P_{a,2} = \frac{V_{a,2}}{T_s} \left[ \frac{i_{a,2}(t_2) + i_{a,2}(t_3)}{2} \right] t_{a,2} \quad (13)$$

If (12) and (13) are divided the following equation is obtained:

$$\frac{P_{a,1}}{P_{a,2}} = \frac{V_{a,1} t_{a,1}}{V_{a,2} t_{a,2}} \frac{i_{a,1}(t_2) + i_{a,1}(t_3)}{i_{a,2}(t_2) + i_{a,2}(t_3)} \quad (14)$$

From (14) can be determined the relation between the powers which the motor restores energy in two different time intervals  $t_{a,1}$  and  $t_{a,2}$  for two different duty cycles  $k_1$  and  $k_2$ .

In Fig. 5 are shown experimentally obtained waveforms for the voltage  $u_M(t)$  (channel 1) and the current  $i_M(t)$  (channel 2) of the DC motor. The DC motor is controlled by an IGBT DC/DC power converter, for two values of the duty cycle  $k_1$  and  $k_2 > k_1$ . For collecting the restored power from the motor for the time interval  $t_a$ , an electronic circuit is built which operates only in this time interval as in Fig. 3.

From the waveforms shown in Fig. 5 can be concluded that the amplitude of the excitation pulse  $V_i$ , the amplitude of the generated voltage  $V_{a,i}$  and the time interval  $t_{a,i}$  (in which the motor restores energy), are greater in case when the duty cycle is lower (waveforms shown in Fig. 5a); And also, the time interval  $t_i$  is short in the case when the duty cycle is lower (waveforms shown in Fig. 5a).

From (12) - (14) and from the waveforms in Fig. 5, can be concluded that when  $k_1 < k_2$ ,  $t_{i,1} < t_{i,2}$ : 1) For lower duty cycles (the case with waveforms for  $k_1$  in Fig. 5a), the voltage which the motor generates  $V_{a,1}$ , the average value of the current  $i_{a,1}$  in the time interval  $t_{a,1}$ , are greater than the voltage  $V_{a,2}$ , the average value

of current  $i_{a,2}$  in the time interval  $t_{a,2}$  (the case with waveforms for  $k_2$  in Fig. 5b). The power  $P_{a,1}$  which the motor restores in the time interval  $t_{a,1}$  is greater than the power  $P_{a,2}$  which the motor restores in the time interval  $t_{a,2}$ .

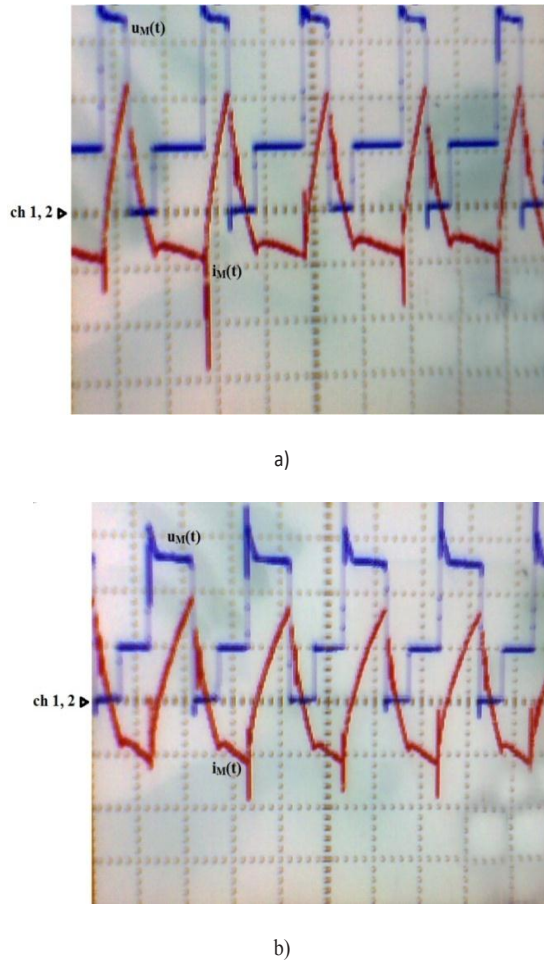


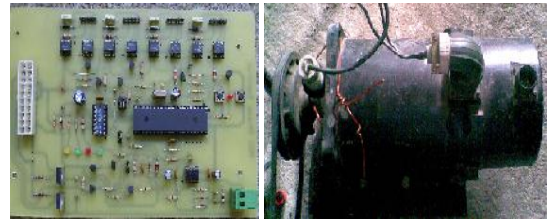
Figure 5: Waveforms of the voltage  $u_M(t)$  (channel 1: H-250  $\mu$ S/div, V -50V/div) and current  $i_M(t)$  (channel 2: H-250  $\mu$ S/div, V -4A/div) of DC motor, controlled from an IGBT DC/DC power converter: a) for duty cycle  $k_1$ , b) for duty cycle  $k_2 > k_1$ .

From this can be concluded that when the DC motor operates in pulse mode and a lower duty cycle, the amount of the restored energy in the time interval  $t_{a,i}$  is greater.

## EXPERIMENTAL RESULTS

In the measurement phase and testing IGBT DC/DC power converter is used with switching frequency  $f_s = 1.972$  kHz (period  $T_s = 1/f_s = 507.10$   $\mu$ s) and electronic circuit with 4-bit resolution [8], [9]. This provides that the excitation pulses of the IGBT

transistor gate (which is in the time interval  $t_i$ ) is in the range of  $T_s/16 = (507.10/16)$   $\mu$ s = 31.70  $\mu$ s to  $16^* T_s/16 = 507.10$   $\mu$ s. In the experimental test DC motor with permanent magnet is used with the following features: rotor voltage  $V_M = 100$  V, rotor current  $i_M = 30$  A, power  $P_M = 3$  kW and  $n_M = 1600$  rpm. In Fig. 6 are shown the control electronic circuit of the DC/DC converter and the DC motor which is used in the experimental measurements.



a) b)  
Figure 6: a) Control electronic circuit of the DC/DC converter and b) DC motor used in the experimental measurements.

First, motor with connected output mechanical loads is analyzed for two values of the duty cycle  $k_1 = 0.25$  and  $k_2 = 0.44$ . The average values of the input DC voltage are determined and thus the power which the motor receives for both duty cycles is the same.

Therefore, a DC voltage source with regulated rectifier connected to the input of the DC/DC converter is used. For duty cycle  $k_1 = 0.25$  the measured input power is  $P_{in} = 385$  W, the average value of the input voltage in the DC/DC converter is  $V_{in} = 172$  V, and the motor shaft speed is  $n = 780$  rpm. For duty cycle  $k_2 = 0.44$ , it is measured  $P_{in} = 385$  W,  $V_{in} = 132$  V and  $n = 780$  rpm.

The waveforms of the voltage  $u_M(t)$  and the current  $i_M(t)$  of the DC motor, controlled by an IGBT DC/DC power converter for duty cycle  $k_1 = t_i/T_s = (4T_s/16)/T_s = 0.25$  are shown in Fig. 5a and the waveforms for duty cycle  $k_2 = (7T_s/16)/T_s = 0.44$  are shown Fig. 5b.

Based on the waveforms shown in the Fig. 5a and 5b, as and in (9) - (14), in Table I and Table II the values of  $t_i$ ,  $t_a$ ,  $t_p$ ,  $V_i$ ,  $V_a$ ,  $i_i(0)$ ,  $i_i(t_i)$ ,  $i_a(t_2)$ ,  $i_a(t_3)$ ,  $P_{M,i}$ ,  $P_{a,i}$ ,  $P_{M,1}/P_{M,2}$ ,  $P_{a,1}/P_{a,2}$  and  $n$  are given.



From the data presented in Table 1 and Table 2 can be concluded that the power which the motor receives during the time interval  $t_i$  is almost the same for both duty cycles  $k_1$  and  $k_2$ ; and that the power which the motor restores in time interval  $t_a$  is greater when the duty cycle is lower.

**TABLE-1**  
**THE VALUES OF  $t_i, t_p, t_a, V_i, V_a, i_i(0), i_i(t_1), i_i(t_2), i_i(t_3)$**

$k$	$t_i(\mu s)$	$t_p(\mu s)$	$t_a(\mu s)$	$V_i(V)$	$V_a(V)$	$i_i(0)(A)$	$i_i(t_1)(A)$	$i_i(t_2)(A)$	$i_i(t_3)(A)$
0.25	126.8	120.4	260	172	58	-1.2	8.4	3	3.6
0.44	221.9	140.2	145	132	49	-1.6	7	3.3	4

**TABLE - 2**  
**THE VALUES OF  $P_{M,i}, P_{a,i}, P_{M,1} / P_{M,2}, P_{a,1} / P_{a,2}$  and  $n$**

$k$	$P_{M,i}(W)$	$P_{a,i}(W)$	$P_{M,1} / P_{M,2}$	$P_{a,1} / P_{a,2}$	$n(rpm)$
0.25	154.8	98.1	$\approx 1$	1.92	1200
0.44	156	51.1			1200

CONCLUSIONS

In this paper, theoretical analysis of DC motor operation in pulse mode and low duty cycle is represented. With this theoretical analysis and from experimentally obtained waveforms of the DC motor voltage and current, controlled by a DC/DC converter for different duty cycles is determined the power which the motor receives from the power source, and also the power which it restores in time interval without excitation pulse. The results of the theoretical analysis are supported by the results from experimental measurements.

The results of the theoretical analysis and experimental measurements show that when the DC motor operates in pulse mode, the greater amplitude of the excitation pulse and lower duty cycle, the amount of the restored motor energy is greater.

Increasing the amount of the restore motor energy and restoring it to the circuit back, contributes to improve the efficiency of the system DC/DC converter – DC motor.

The results presented in the paper are applicable for DC motors modes that has periods in which the motor operates without load. This is a good basis for future research in the applications of DC motors in industrial machinery with fans and pumps.

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